HTS Motors in Aircraft Propulsion: Design Considerations

Philippe J. Masson, Danielle S. Soban, Eric Upton, Jules E. Pienkos, and Cesar A. Luongo

***Abstract*—Current high temperature superconducting (HTS) wires exhibit high current densities enabling their use in electrical rotating machinery. The possibility of designing high power density superconducting motors operating at reasonable temperatures allows for new applications in mobile systems in which size and weight represent key design parameters. Thus, all-electric aircrafts represent a promising application for HTS motors. The design of such a complex system as an aircraft consists of a multi-variable optimization that requires computer models and advanced design procedures. This paper presents a specific sizing model of superconducting propulsion motors to be used in aircraft design. The model also takes into account the cooling system. The requirements for this application are presented in terms of power and dynamics as well as a load profile corresponding to a typical mission. We discuss the design implications of using a superconducting motor on an aircraft as well as the integration of the electrical propulsion in the aircraft, and the scaling laws derived from physics-based modeling of HTS motors.**

***Index Terms*—Aircraft design, all-electric aircraft, electric propulsion, superconducting motor.**

I. Introduction

HISTORICALLY, aircraft have been designed using a great deal of regression using data from past designs. While time- and resource-efficient, this method is unable to adapt to sudden changes in technology, such as those accompanying a radical change in the fundamental generation of propulsion. Modern design techniques employ technology evaluation and an increased reliance on physics-based models, as well as the quantitation of risk and uncertainty. Specifically, propulsion technologies have been critical in the development of new aircraft, with leaps in system performance following sudden developments in propulsion technologies. For example, the change from aircraft with reciprocating engines and propellers to jets heralded the beginnings of affordable, efficient air transport for the general public, not to mention a large leap forward in military aircraft capability. Changes of this magnitude affect not only system performance but also the way the aircraft are perceived and designed, expanding the realm of mission possibilities. Electric propulsion has the potential to be the next significant leap in aircraft propulsion technology.

II. All-Electric Aircraft Development Effort

Rapidly evolving technologies aimed at creating electrical power with minimal environmental impact have encouraged the study of electrical propulsion as a way to power new types of aircraft. Historically, electric power has been too heavy for use in aircraft propulsion. Low energy densities of power storage mediums and large, heavy motors have kept electrical propulsion on the ground. Advances in motors, fuel cells, batteries and capacitors, however, have developed these technologies to the point where future use in aircraft can begin to be considered. Electric propulsion offers several advantages. Low vehicle emissions, in terms of both pollutants and noise, is possible with no on-board combustion. The increased thermodynamic efficiencies involved with fuel cells and commercial ground power generation also promises a more effective use of fuel resources and the ability to use alternate sources of power that would be impractical for use on aircraft, such as solar power or even nuclear power generation. Military and scientific applications are also abundant. Extended mission times help scientific and military missions while low observability (made possible by elimination of hot, noisy exhausts) would help improve the effectiveness of military aircraft.

A. Design Considerations

Powered flight is an extremely weight-critical exercise. Modern jet engines, for example, are not very efficient, but their relatively light weight allows for the design of aircraft capable of carrying large loads over extended distances far more rapidly than any other form of transportation. Similarly, the structures in modern aircraft are designed to maximize strength while minimizing weight. The placement of this weight throughout the structure of the aircraft is also important, as the controllability of the aircraft hinges on the placement of major components relative to the aerodynamic control surfaces—having too much weight in the wrong place could make the aircraft unsafe.

Volume is nearly as critical, with the aerodynamic properties of an aircraft being directly related to its shape and surface area. Minimizing the surface area of an aircraft's primary structure is one of the keys to increasing its efficiency in flight. Traditional aircraft have a fairly well defined collection of primary components, and each of these is similarly well defined in its use, but adding the components of an electrical propulsion system adds another level to the integration problem. Power conditioning and integration with existing electrical subsystems

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becomes more important while traditional weight estimations become useless with the different weight distributions inherent in electrical propulsion designs.

B. Electric Aircraft Design Approach

Aircraft are traditionally modeled at several levels. Initial designs are synthesized using any of a variety of techniques, ranging from empirical extrapolations of existing data to sophisticated computer-based analyses. Proposed designs are then measured against performance constraints, such as the ability to fly at a given speed or climb at a certain rate. Designs meeting these constraints are then flown through finely discretized simulated missions, where fuel requirements are determined and weights are roughly calculated. This produces the overall size of the proposed design. The sized design is then evaluated against the customer desires, and the process iterates until a final design is reached and then refined until production begins.

Traditional aircraft design tools, however, are unable to account for and model the significant changes inherent in aircraft designed around electric propulsion systems. Battery-dependent systems, for example, do not have a significant weight change during flight, rendering useless the many range calculation routines dependent on changes in aircraft weight due to the burning of fuel (and ejecting of the waste stream).

Mission analysis can be done, however, with special adaptations to handle changes due to integration of electrical propulsion. NASA's Flight Optimization Software (FLOPS), used for this study, is designed to model aircraft powered exclusively by jet or reciprocating internal combustion engines. To accurately model aircraft with electric propulsion, FLOPS must be modified.

For this work, power-based sizing routines have been developed external to the primary sizing code to treat the propulsion system's overall power storage ability as the primary factor deciding range rather than the burning of fuel. Adjustments to component weights within mission analysis software are relatively straightforward, and allow the lower power densities of electric aircraft to be easily reflected in mission performance.

The inclusion of electric propulsion in the mission model, then, becomes primarily a matter of correct weight estimations and efficiency of power generation. Once a power generation model has been constructed, a method must be devised to transmit that power to propulsive force.

A unified electric propulsion system requires a motor of some sort to convert electrical energy into the necessary propulsive thrust. Traditional electric motors have historically been large and heavy—far too heavy to properly propel a usable aircraft. Recent developments in superconducting materials have made high temperature superconducting motors increasingly feasible as a propulsion system option.

III. HTS Propulsion Model

A. HTS Motor

Electrical motors are electro-mechanical converters that can be used to drive a propeller. The thrust needed for propulsion can be converted in terms of forces on the blades and then in terms of torque applied to the shaft. This propulsion power needs to be generated from electrical power. The model needs links from the propulsion power and rotation speed of the propeller to the size and weight of the motor (Fig. 1).

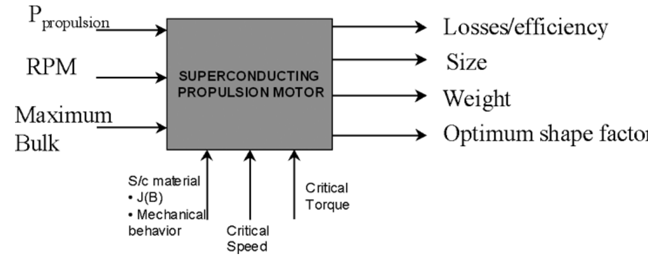

Fig. 1. Inputs and outputs of the electrical motor model.

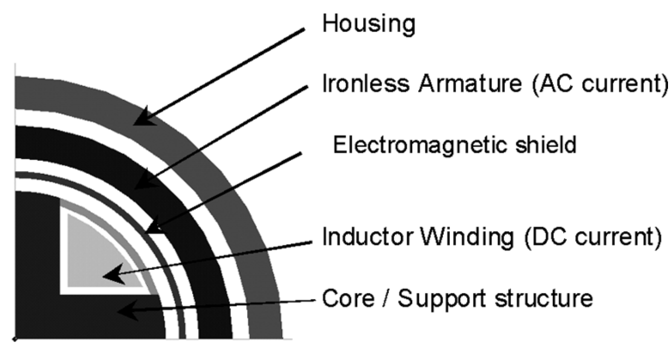

Fig. 2. Simplified geometry implemented in FEA software.

Electromagnetic torque stems from the interaction of the no-load field B_r^0 provided by the inductor and the electric loading of the armature K_{arm} as stated in following equation.

$$T = \sqrt{2} B_r^0 K_{arm} \pi r_{arm}^2 L \tag{1}$$

Power is calculated from the electromagnetic torque and the rotation speed as follows.

$$P = T\Omega \tag{2}$$

The no-load magnetic field is produced by the superconducting inductor made of wound coils; the superconducting wire has a nonlinear characteristic Jc(B) linking its critical current density to the applied flux density. In order to calculate the operating point of the wire, we implemented a synchronous configuration in finite element analysis software as presented in Fig. 2.

The implemented geometry is simplified and composed of the main elements needed for a preliminary design.

Equation (1) provides an estimation of the active volume of the machine for a given power; once the geometry is entered and the different sources and boundaries are defined, we calculate the maximum flux density on the superconducting wire as presented in Fig. 3.

The support structure is not magnetic, which increases the magnitude of the magnetic field applied to the wire. Once the location of the maximum field is identified, the load curve of the magnet can be plotted, and the operating point of the wire can be

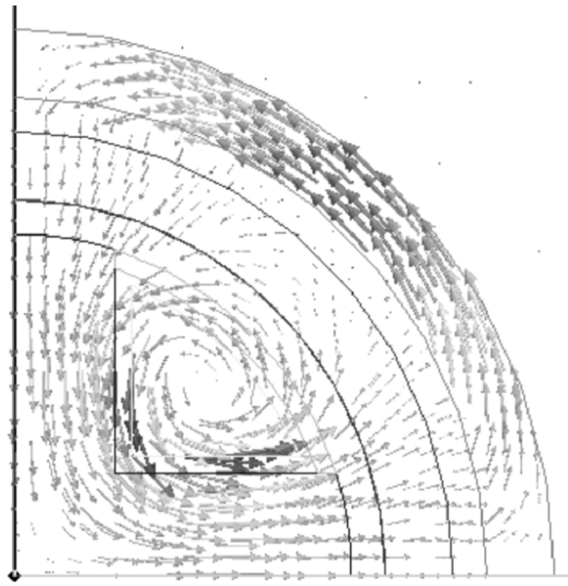

Fig. 3. Flux distribution in the machine.

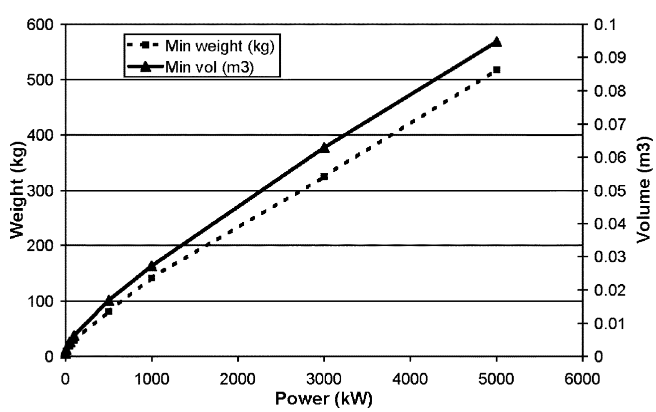

Fig. 4. Sizing laws of HTS synchronous motors L/R constant.

determined from the Jc(B) characteristic. We typically consider operation at 80% of the critical current and a filling ratio of 85% of the coils. Then, a parametric investigation is performed with the objective of finding the parameters leading to a minimum weight or volume of the system.

From the preliminary sizing of synchronous HTS motors for different level of power, we could plot curves of estimated weight versus power and volume versus power, for instance for four poles at 3000 RPM as shown in Fig. 4. These curves can be fitted and provide analytical equations usable in an aircraft optimization software. For large power levels, weight and volume are almost proportional to power.

B. Cooling System

The superconducting motor has to operate at cryogenic temperature and so cannot operate without a cooling system. The cooling system extracts the heat either through a cryorefrigerator or via a liquid cryogen.

1) Cryocoolers: Cryocoolers provide a cold head that can be connected to a conduction cooling apparatus thermally bonded to the inductor. Cryocoolers represent a very simple cooling

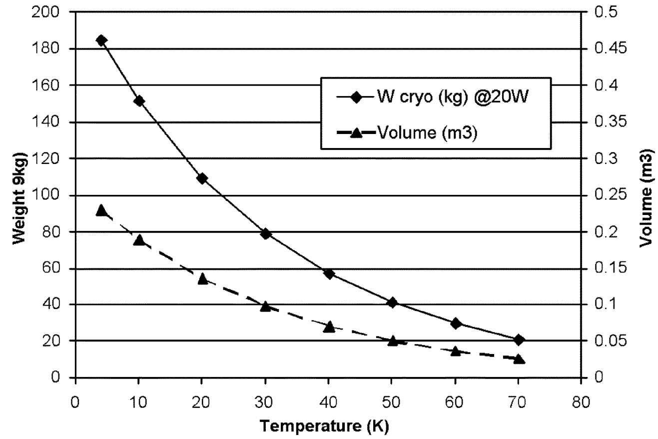

Fig. 5. Scaling model for existing cryocoolers.

Fig. 6. Cessna 172SP (source: Cessna Aircraft Company).

method since they only require a power source to operate. The user does not see the cooling system and does not require special skills to operate the system. However, cryocoolers exhibit very low efficiency—lower than 10%, and are quite heavy and bulky. Losses in the cold part of HTS motors are typically in the range of 20 W. A sizing model can be deduced from cryocoolers currently available on the market; the scaling model is represented in Fig. 5. One has to take in consideration that the available cryocoolers have been developed for ground applications and therefore are not optimized for use in mobile, weight-critical applications. Light devices need to be designed for this specific application.

2) Cryogenic Bath: Liquefied gas can also be used to cool down superconducting devices; the losses of the motors imply the evaporation of a certain amount liquid that needs to be re-condensed. Usually a closed loop of refrigerant is used and a cryocooler compensates the losses. However, if fuel cell stacks generate electrical power, a cryogenic storage of hydrogen may be available onboard and liquid hydrogen could be used to cool down the motor thus reducing the weight of the cooling system to its minimum.

IV. Test Case: Cessna 172 Type Aircraft

A. Propulsion Requirements

The aircraft chosen as baseline for this study is the Cessna 172. The most popular aircraft ever made, it seats four, weighs about 1200 kg fully laden, and cruises at around 200 kph. It is powered by an air-cooled reciprocating engine displacing 5.9 l and producing between 120–135 kW (depending on model). The widespread popularity, relatively simple architecture and modest power requirements make the 172 an appropriate representative aircraft for this exercise. A sample 172 can be seen in Fig. 6.

B. Typical Mission Profile

The 172's typical mission is extremely simple: takeoff, climb to the desired cruise altitude, fly at that altitude for a certain distance, then descend and land. Typically, the 172 is flown at full power for takeoff climb, and then, due to the effects of altitude on the power output of the engine and the engine's own efficiency characteristics, at about 75% power for the remainder of the flight. Full power should be available at any time during the flight in the event of emergency.

The 172 requires approximately 45% power to maintain level flight, so any situation involving a drop in available power below that level would result in a forced landing.

C. Sizing of the Superconducting Propulsion System

Electrical propulsion needs to be designed as a global system including both the superconducting motor and its cooling system. Fig. 7 represents a plot of the weight of the motor and of the cooling system using a cryocooler versus operating temperature for a heat load of 20 W. We can notice that an optimum operating temperature leading to a minimum weight can be determine from the scaling model. An operating temperature of about 55 K seems to correspond to the optimum possible with currently available cryocoolers. This shows that second generation HTS conductors that can operate at 50 K would be the logic choice for the design of a propulsion motor in the range of 200 HP. According to the developed model, a superconducting propulsion motor for the Cessna 172 would weigh about 60 kg and would use a cryocooler of about 35 kg. The total system would weigh less than 100 kg to be compared to the conventional combustion engine that weighs about 160 kg. We can notice that an optimum operating temperature leading to a minimum weight can be determine from the scaling model. An operating temperature of about 55 K seems to correspond to the optimum possible with currently available cryocoolers. This shows that second generation HTS conductors that can operate at 50 K would be the logic choice for the design of a propulsion motor in the range of 200 HP. According to the developed model, a superconducting propulsion motor for the Cessna 172 would weigh about 60 kg and would use a cryocooler of about 35 kg. The total system would weigh less than 100 kg to be compared to the conventional combustion engine that weighs about 160 kg.

Obviously, the first question to be asked by aircraft designers will be, "Where does the electricity come from?"

With a weight of 100 kg, the HTS motor is lighter than the existing combustion engine, but it does not provide its own power.

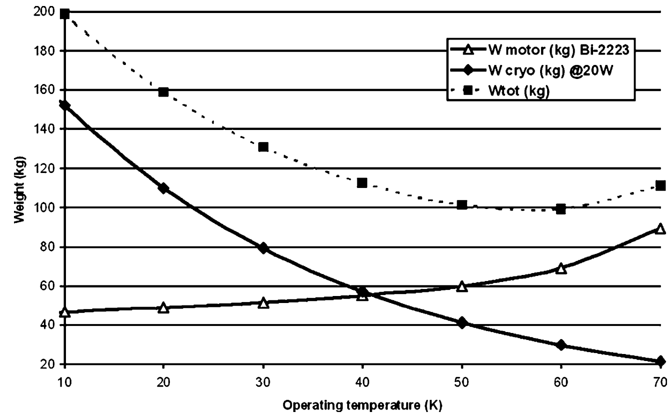

Fig. 7. Weight of the system versus operating temperature for a heat load of 10 W.

Electrical power suitable for the HTS motor could come from a variety of sources: fuel cells, batteries, capacitors, or even solar panels. These extra systems, and the secondary systems they will require to sustain them, do add weight, and the weight advantage of the HTS motors will quickly disappear. The solution, of course, is a lighter motor. With cryocoolers optimized for lightweight aircraft applications, weight can be saved, and with advances in fuel cell power generation, further weight savings may make a HTS-powered aircraft possible in the near future.

V. CONCLUSION

Major advances in aircraft technology are often the result of major advances in propulsion technology. The use of electric motor technology on aircraft could be one such major advance. In order to make electric propulsion viable and feasible, assessments of weight, volume, and power generation must be accurately determined. The HTS motor is a possible candidate for electric motor application in aircraft. While more complex than similarly sized, ordinary electric motors, HTS motors offer lower weight, packaging flexibility and increased power density that could prove useful in aircraft applications. This paper examines one simplified application of HTS technology within an existing aircraft system. A full analysis of HTS integration into a functional aircraft would require additional study and consideration of electrical power generation.

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